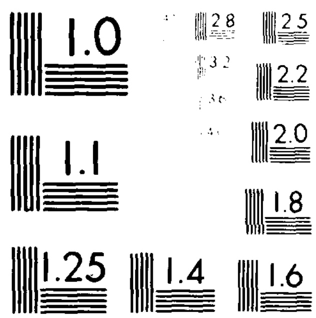
AD-A090 312 NATIONAL BUREAU OF STANDARDS WASHINGTON DC FRACTURE A--ETC F/G 11/2
HOT EROSION OF GLASS.(U)
JUN 80 S M WIEDERHORN, B J HOCKEY
UNCLASSIFIED NBSIR-80-2034 NL

1 OF 1
AD A
090312

END
DATE
FILMED
11-80
DTIC



MICROCOPY RESOLUTION TEST CHART

(14) NBSIR-80-2034

(6) # HOT EROSION OF GLASS.

(10) S. M. Wiederhorn and B. J. Hockey

Fracture and Deformation Division
National Measurement Laboratory
Center for Materials Science
National Bureau of Standards
U.S. Department of Commerce
Washington, D.C. 20234

Interim Report,

(11) June 1980

Prepared for
Office of Naval Research
Metallurgy and Ceramics Program
Department of the Navy
Arlington, VA.

U.S. DEPARTMENT OF COMMERCE, Philip M. Klutznick, *Secretary*

Luther H. Hodges, Jr., *Deputy Secretary*
Jordan J. Baruch, *Assistant Secretary for Productivity, Technology, and Innovation*

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

411 L 91

HOT EROSION OF GLASS

S. M. Wiederhorn and B. J. Hockey

ABSTRACT

In this paper the effect of plastic flow on the erosion of soda-lime-silicate glass at elevated temperatures is investigated. Although the erosion of glass at 500°C and 600°C is still basically a brittle process, viscous relaxation of glass during impact reduces the driving force for fracture and thus the size of the chips that are formed during erosion. As a result, the erosion rate of glass at 500°C or 600°C is decreased by a factor of 2 compared to that measured at room temperature. To completely eliminate fracture during erosion, a temperature of ~800°C is estimated for soda-lime-silicate glass.

INTRODUCTION

Glass at room temperature is usually considered to be an ideally elastic solid. When subjected to distributed loads, glass always returns to its initial size and shape provided fracture does not intervene. By contrast, metallic or polymeric materials will generally deform plastically when stressed beyond their elastic limit. Because of its elastic behavior, glass has been used by a number of investigators to illustrate the response of elastic materials to impact by solid particles. It is a well documented fact that the erosion of brittle materials occurs by crack formation at the impact site, and that chipping of material from the surface accounts for the loss of materials during erosion [1-5]. As a consequence of this mechanism, erosion is greatest for brittle materials when impact occurs at normal angles of

incidence [2,4]. This behavior differs from that observed for metals and polymers; for these materials, erosion occurs primarily by plastic cutting or ploughing mechanisms and the rate of erosion is greatest at an impact angle of $\sim$15 to 20 degrees [5]. The dependence of erosion rate on impact angle has been used extensively to distinguish between erosion that is primarily brittle and erosion that is primarily ductile.

Despite the fact that brittle materials (such as glass) behave in a elastic manner when subjected to distributed loads, concentrated loads, such as those developed during quasi-static indentation or impact with angular, solid particles, can cause plastic flow [1,4]. The small, highly localized plastic deformation that occurs during these contact situations is very important to the erosion process, since it affects the development of cracks and surface chips. As a consequence, recent theories for the erosion of glass and other brittle materials have related the volume of material lost by surface chipping both to fracture toughness - as represented by the critical stress intensity factor, K_{IC} - and to the resistance to plastic flow - as represented by the hardness - of the target material [1,5]. These elastic-plastic theories, moreover, predict a minimum impact load below which chipping should not occur. They, thus, provide a basis for explaining Sheldon and Finnie's observation [2] that the erosion of glass changes from a brittle mode to a ductile mode for sufficiently small particles ($\leq 10 \mu m$).

In an effort to further explore the importance of plastic flow to the erosion of glass, the effect of temperature on both impact damage and erosive wear was investigated. Because glass readily softens at elevated temperatures, substantial changes in impact erosion behavior were anticipated. This paper presents the results of that study.

PROCEDURE

Experiments were conducted on soda-lime-silicate glass using SiC particles with a nominal size of 150μm. Studies were conducted at room temperature, 500°C, 600°C and 680°C, using erosion equipment that has been described elsewhere [6]. The glass selected for study had a glass transition temperature of ∿470°C and an annealing temperature of ∿510°C, so that the high temperature erosion measurements were made at temperatures at which stress relaxation occurred easily. Specimens eroded at 600°C showed clear signs of distortion by viscous flow; specimens eroded at 680°C gave indication of gross changes in shape due to viscous flow. Plastic flow and stickiness of the glass precluded the measurement of the erosion rates at 680°C; however, optical micrographs of the impact sites were obtained. Impact angles ranging from 15° to 90° and particle velocities ranging from ∿40 m/s to ∿125 m/s were used in these studies. To illustrate the type of damage that occurs as a result of impact, optical and scanning electron micrographs were obtained for representative exposure conditions.

RESULTS

Under all erosion conditions damage to the target surface consisted of plastic impressions, arrested cracks, and chipped areas where material was removed from the surface. At normal impingement, crack formation at the point of impact dominated the erosion process, Fig. 1. Two types of cracks could be distinguished: one type lying on planes perpendicular to the target surface; the other type lying on planes roughly parallel to the surface [1,4,5]. The first type of cracks, known as radial or median cracks; are mainly responsible for strength degradation in glass. The second type of cracks, known as lateral cracks, lead to the formation of chips and are primarily responsible for the erosion of glass. Although radial and lateral cracks also

form during impact at elevated temperatures, their formation and growth was affected by the enhanced plastic properties of the glass. Compared to room temperature results, a much larger fraction of impact sites produced at 500°C and above showed no indication of cracking, indicating a relative increase in impact fracture threshold load. The size of cracks produced at these temperatures was measurably less than that produced at room temperature, and the lateral cracks, in particular, were more often arrested in the glass (compare, for example, Figs. 1a and 1b). This reduced tendency for chipping usually led to the retention of the central, plastic impact impression at 500° and 600°C, whereas at 25°C, the plastic impressions are usually indistinct or lost due to chipping within the contact area. Also, when examined by transmitted light microscopy, the margins of arrested lateral cracks produced at elevated temperature are much more distinct than those produced at room temperature. This suggests that at elevated temperatures, crack-tip blunting by plastic flow has occurred. In agreement with this interpretation, the tips of surface-intersecting cracks produced at 600°C appear rounded rather than sharp (Fig. 2). At 680°C, the process of plastic flow during erosion is further accelerated by the less viscous nature of the glass. Plastic impressions at the impact site are more pronounced than those at either 500° or 600°C, and cracks that are formed are closely arrested in the vicinity of the contact impression (Fig. 3). Thus, while cracks can be produced by impact at 680°C, they cannot propagate easily because of viscous relaxation of the glass.

At oblique angles of impact (≈15°), plastic flow plays a greater role in the erosion process. In all cases, the impact craters are clearly elongated in the direction of particle travel (Fig. 4). While the majority of oblique

impacts at room temperature result in cracking, there is a definite decrease in the incidence as well as the extent of cracking with decreasing particle velocity. Thus even at room temperature (Fig. 4a), material removal by a plastic ploughing or cutting process occurs and contributes to the erosion process. At 15° impingement, the cracks produced were predominantly of the lateral type, and they most often extended from the side edges of the elongated impressions. However, impact sites at which deep particle penetration occurred (usually at high velocities) often exhibited lateral cracks extending from the exit edge of the impact crater. This crack geometry seemed to form as a result of the wedging action of the impacting particle against the side of the plastically formed crater.

As expected, the plastic response of the glass to oblique-impingement erosion is enhanced at elevated temperatures. At 500° and 600°C, well over half of the impact sites are crack free, indicating plastic removal mechanisms contribute significantly to the erosion process. Lateral crack formation tends to form primarily at the exit edge of the impact crater indicating deeper penetration and the importance of the wedging action of the impacting particles (Fig. 4b). As was observed at room temperature, crack formation at elevated temperatures is enhanced as the particle velocity is increased; however, at all velocities, cracking is more severe at room temperature than at elevated temperatures.

A particularly interesting observation made in this study was that glass melted locally as the result of solid particle impact. Melting was indicated by the formation of glass fibers drawn from the exit edge of the impact crater (Fig. 4b). These fibers were observed both at room temperature and at

elevated temperatures. At 500°C and 600°C, fiber formation was more common than at room temperature. The use of stereographic micrographs also indicated fiber formation at normal impact angles for elevated temperature exposure. In addition to fiber formation, topographical features within impact craters suggest that pools of molten glass had formed during the impact process. These experimental results suggest that substantial temperature rises occur when a solid particle impacts the surface of glass. As discussed elsewhere by Lawn et al. [7], localized temperatures of ∿900°C are expected at the point of impact in soda-lime-silicate glass. A temperature rise of this magnitude would explain the observation of surface melting during the erosion of this glass.

Considering the microstructural evidence obtained for plastic deformation in glass during single-particle impact, an effect of plastic flow on the erosion of glass is expected. This expectation is supported by measurement of erosion rates as a function of temperature, impact velocity, and impact angle. Figure 5a shows that at 15° and 90° impact, the erosion rate at 500°C was approximately one-half that found at room temperature regardless of impact velocity. Results similar to those at 500°C were obtained for glass eroded at 600°C. This decrease in erosion rate is due to the enhanced role of plastic deformation in the erosion of glass at high temperatures. These results are consistent with the microscopic observations that chip formation is suppressed at 500°C and 600°C and that when chips of glass do form at the impact site, they are smaller at elevated temperatures than at room temperature.

Despite the observation of plastic deformation during the erosion of glass at 500°C and 600°C, the dominant process of material removal still appears to be brittle in nature. This conclusion is supported by the fact that, although reduced in magnitude, chipping is still a major factor in material removal,

especially at normal and near normal angles of particle impingements. The fact that erosion is basically brittle in nature is also supported by the dependence of the erosion rate on impingement angle, which is clearly a maximum at 90° impingement (Fig. 5b). Therefore, although plastic flow of the glass plays a role in reducing the rate of erosion at 500°C and 600°C, the erosion process in glass is still brittle in character.

DISCUSSION

Glass behaves in a brittle fashion during hot erosion because it is viscoelastic at elevated temperatures. Stress relaxation in glass is time dependent, so that the response of the glass to impact will be brittle if the impact process occurs at a faster rate than the relaxation processes. Impact times in materials that suffer plastic flow duirng impact are typically of the order of 10^{-5} s or less [8]. A qualitative measure of relaxation in glass at elevated temperatures is given by the relaxation time, τ, which depends on the shear modulus, μ, and the viscosity, η, of the glass: $\tau = \eta/\mu$. Glass is expected to behave in complately ductile manner during erosion when $\tau < 10^{-5}$ s. For the glass used in the present study ($\mu \sim 30$ GPa) a temperature of the order of 800°C would be required for completely ductile behavior. This result is consistent with our observation that crack formation still occurs during impact at temperatures as high as 680°C.

Results of the present study clearly show that the size of cracks formed during impact are limited by plastic relaxation at temperatures as low as 500°C and 600°C. Since the lateral cracks form after the impact event [5], this result suggests that relaxation of the driving forces for fracture is rapid enough to arrest the cracks formed during impact. At 600°C, $\eta \sim 10^9$ Pa · s (10^{10} poise) and the relaxation time is approximately 0.034s. Since the cracks

propagate approximately 100μm at this temperature, the mean propagation velocity for these cracks must be $\sim 3 \times 10^{-3}$ m/s for crack arrest to have occurred. This estimate of the rate of growth of lateral cracks during impact has yet to be confirmed by direct experimental observation.

REFERENCES

[1] Evans, A. G., Gulden, M. E., and Rosenblatt, M., Impact Damage in Brittle Materials in the Elastic Plastic Response Regime, Proc. Rog. Soc. (London) A361 (1978) 343-365.

[2] Sheldon, G. L., and Finnie, I., On Ductile Behavior of Nominally Brittle Materials During Erosive Cutting, Trans. A.S.M.E.: J. Engr. for Ind., 88, (1966) 387-92.

[3] Evans, A. G., Impact Damage in Crystals, in: Bradt, R. C., Hasselman, D. P. H., and Lange, F. F. (Eds.) Fracture Mechanics of Ceramics 3 (Plenum Press, New York, 1978).

[4] Hockey, B. J., Weiderhorn, S. M. and Johnson, H., ibid., Erosion of Brittle Materials by Solid Partical Impact.

[5] Ruff, A.W. and Wiederhorn, S.M. Erosion by Solid Particle Impact, in: C. M. Preece (ed.), *Treatise* on Materials Science and Technology, Vol. 16, Erosion (Academic Press, New York, 1979).

[6] Wiederhorn, S. M. and Roberts, D. E., A Technique to Investigate the High Temperature Erosion of Refractories, Bull. Am. Ceram. Soc. 55 (1976) 185-9.

[7] Lawn, B. R., Hockey, B. J. and Wiederhorn, S. M., Thermal Effects in Sharp-Partical Contact, to be published.

[8] Tabor, D., The Hardness of Metals, Oxford University Press, London, 1951.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Hot Erosion of Glass		5. TYPE OF REPORT & PERIOD COVERED Interim Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) S. M. Wiederhorn and B. J. Hockey		8. CONTRACT OR GRANT NUMBER(s) N00014-79-F-0030
9. PERFORMING ORGANIZATION NAME AND ADDRESS National Bureau of Standards Washington, D. C. 20234		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61153N, RR 022-02-01 (471)
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research 800 North Quincy Street Arlington, VA. 22217		12. REPORT DATE May 1, 1980
		13. NUMBER OF PAGES 15
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report)
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Crack growth, fracture, erosion, glass, strength degradation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In this paper the effect of plastic flow on the erosion of soda-lime-silicate glass at elevated temperatures is investigated. Although the erosion of glass at 500°C and 600°C is still basically a brittle process, viscous relaxation of glass during impact reduces the driving force for fracture and thus the size of the chips that are formed during erosion. As a result, the erosion rate of glass at 500°C or 600°C is decreased by a factor of 2 compared to that measured at room temperature. To completely eliminate fracture during erosion, a temperature of ∿800°C is estimated for soda-lime-silicate glass.

DD FORM 1473 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

S/N 0102-LF-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

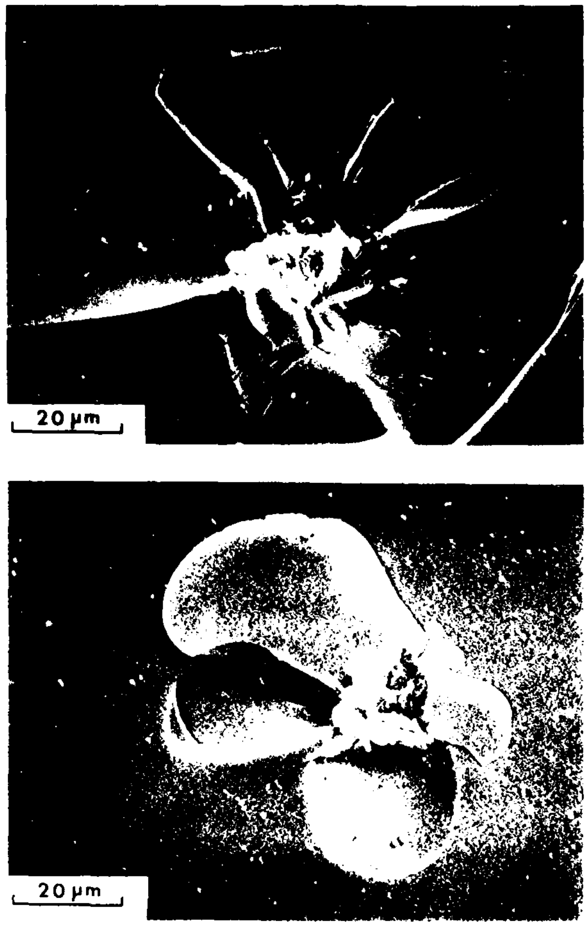


Figure 1. Normal-incidence impact damage in glass at:

a) 25°C and
b) 500°C

Partial velocity, 54 m/s.

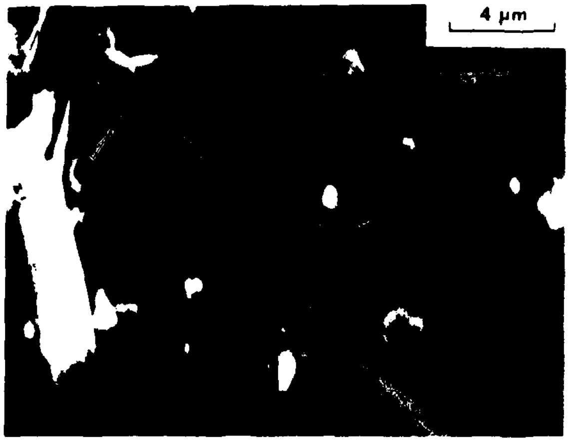


Figure 2. Crack in glass due to impact at 600°C. Note blunt nature of crack growth.

Figure 3. Impact site produced in glass at 680°C.

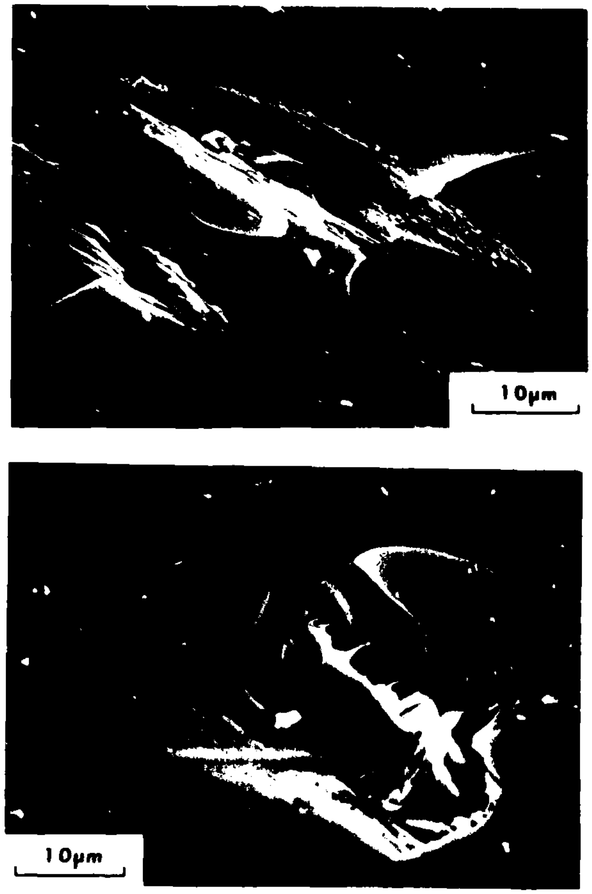


Figure 4. Impact sites in glass produced by oblique (15°) impingement:

a) 25°C and
b) 500°C

Thin fibers drawn from impact in (b) indicate surface melting.

NBS-114A (REV. 9-78)

U.S. DEPT. OF COMM.
BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION OR REPORT NO.
NBSIR 80-2034

2. Gov't Accession No.

3. Recipient's Accession No.

4. TITLE AND SUBTITLE
AD-A090 312

HOT EROSION OF GLASS

5. Publication Date
June 1980

6. Performing Organization Code

7. AUTHOR(S)
S. M. Wiederhorn and B. J. Hockey

8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, DC 20234

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*
U.S. Office of Naval Research
Metallurgy and Ceramics Program

13. Type of Report & Period Covered

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

In this paper the effect of plastic flow on the erosion of soda-lime-silicate glass at elevated temperatures is investigated. Although the erosion of glass at 500°C and 600°C is still basically a brittle process, viscous relaxation of glass during impact reduces the driving force for fracture and thus the size of the chips that are formed during erosion. As a result, the erosion rate of glass at 500°C or 600°C is decreased by a factor of 2 compared to that measured at room temperature. To completely eliminate fracture during erosion, a temperature of ~800°C is estimated for soda-lime-silicate glass.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Erosion; fracture; glass; impact; plastic flow.

18. AVAILABILITY ☒ Unlimited

☐ For Official Distribution. Do Not Release to NTIS

☐ Order From Sup. of Doc., U.S. Government Printing Office, Washington, DC 20402, SD Stock No. SN003-003-

☒ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

19. SECURITY CLASS (THIS REPORT)
UNCLASSIFIED

20. SECURITY CLASS (THIS PAGE)
UNCLASSIFIED

21. NO. OF PRINTED PAGES
15

22. Price
$5.00

USCOMM-DC